Simplified Models of Mixed Dark Matter

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Work with C. Cheung (JCAP02(2014)011 [hep-ph/1311.5896])

Dark Matter: Taking Stock

Dark matter has been an exciting field in recent years!

- Numerous possible signals
  - Annual modulation at DAMA
  - Positron excess at Pamela/AMS
  - Possible signals at CoGeNT, CRESST, CDMS-SI
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  - No consistent signal from other astronomical sources
  - Strong bounds from colliders (on certain models)

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Where to go from here?

Possible Directions?

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Effective theory provides general results

- Powerful for comparing searches of different types
- A large number of theories can be examined concisely
- Description suffers in collider searches
- Relation to relic density is unclear

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Simplifed models can bridge the gap between BSM frameworks and effective theory

The Case for Simplified Models

Collider searches use simplified models appropriate to the search strategy to generalize the analysis

Similarly, dark matter dynamics may be strongly dependent on only a small number of particles

- Direct detection often requires a small number of interactions
- A larger number are required for relic density calculation
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Some models of this type exist already

- Minimal dark matter

Cirelli, Fornengo, Strumia (2006)

- "Squark-bino effective theory"

DiFranzo, Nagao, Rajaraman, Tait (2013); Chang, Edezhath, Hutchinson, Luty (2013); Bai & Berger (2013)

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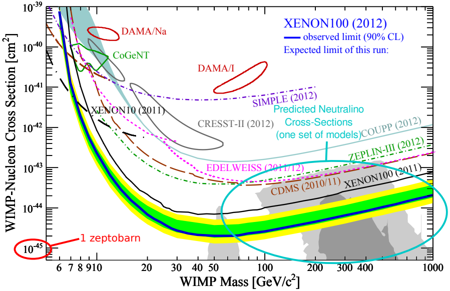

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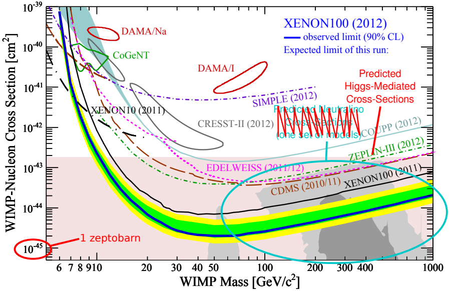

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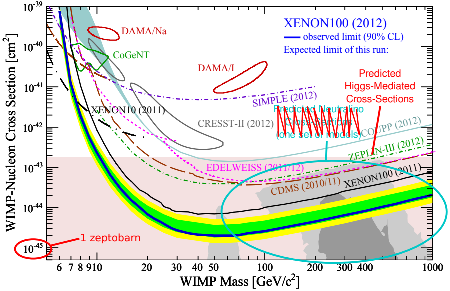


The strength of current and near-future direct detection experiments allows for exploration of DM interacting through the Higgs without requiring the SUSY framework!

Outline

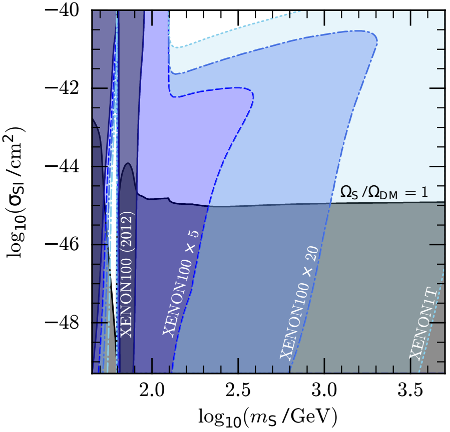
Singlet Dark Matter

A singlet with a Higgs portal is perhaps the simplest DM model

Silveira and Zee (1985), McDonald (1994)

$$V = \frac{1}{2}\mu^2 S^2 + \frac{1}{2}\lambda S^2 |H|^2$$

- Relic density achieved through Higgs-mediated annihilation and annihilation to Higgs
- Coupling strength defined direct detection cross-section
- Within reach at XENON1T up to $M_S \sim 10$ TeV



J. M. Cline, K. Kainulainen, P. Scott, and C. Weniger

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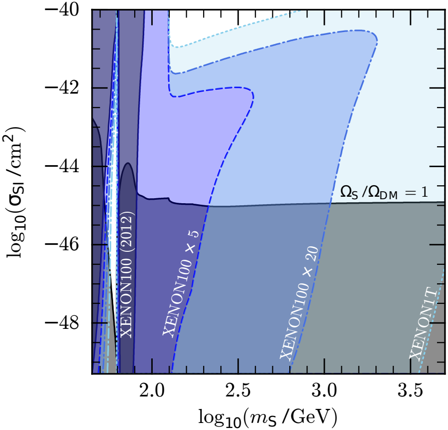
- What about non-singlets?



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Minimal Dark Matter

Dark matter charged under $\mathrm{SU}(2) \times \mathrm{U}(1)$ has the correct relic density at a particular mass through gauge interactions

- Annihilation through W- and Z-bosons has characteristic size
- Mass depends on representation and spin, and increases for higher $\mathrm{SU}(2)$ representations

Quantum numbers			DM can	DM mass	$m_{DM^\pm} - m_{DM}$	Events at LHC	σ_{SI} in
$SU(2)_L$	$U(1)_Y$	Spin	decay into	in TeV	in MeV	$\int \mathcal{L}\, dt = 100/\mathrm{fb}$	$10^{-45}\,\mathrm{cm}^2$
2	1/2	0	EL	0.54 ± 0.01	350	$320 \div 510$	0.2
2	1/2	1/2	EH	1.1 ± 0.03	341	$160 \div 330$	0.2
3	0	0	HH^*	2.0 ± 0.05	166	$0.2 \div 1.0$	1.3
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4	1/2	1/2	(LHH^*)	2.4 ± 0.06	347	$5.3 \div 25$	1.6
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Candidates must be self-conjugate to avoid direct detection bounds from Z-boson mediated scattering

- Requires small non-minimality for $Y \neq 0$

Scalar results are altered by additional $|H|^2|\chi|^2$ operators

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Goudelis, Hermann, Stal (2013)

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Simplified models with more freedom are desireable

Moving to Mixed Dark Matter

Mixed DM $\equiv$ Dark matter which is a mixture of multiple states

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We are most interested in mixtures of states with different $\mathrm{SU}(2)$ representations

- Mixing requires Higgs vev insertions
- Produces a Higgs coupling

$$c_{h\chi\chi} h\chi\chi \text{ (fermion)} \qquad a_{h\chi\chi} h\chi\chi \text{ (scalar)}$$

- Generalization of "bino-Higgsino" mixing in the MSSM but with arbitrary representation, spin, and Higgs couplings

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Will consider three models

Singlet-Doublet Fermion	Singlet-Doublet Scalar	Singlet-Triplet Scalar

The Singlet-Doublet Fermion Model

Generalization of "bino-Higgsino" mixing in the MSSM or "singlino-Higgsino" mixing in the NMSSM

Cohen, Kearney, Pierce, Tucker-Smith (2012)

- Yukawa terms are no longer tied to gauge couplings or Higgs potential

Field	Charges	Spin
S	$(\mathbf{1}, 0)$	1/2
D_1	$(\mathbf{2}, -1/2)$	1/2
D_2	$(\mathbf{2}, 1/2)$	1/2

- Requires two doublets
  - Provides a doublet mass term
  - Eliminates anomalies

$$-\mathcal{L} \;=\; \frac{1}{2} M_S S^2 + M_D D_1 D_2 + y_{D_1} S H D_1 + y_{D_2} S H^\dagger D_2 + h.c.$$

- A polar representation makes formulation simpler

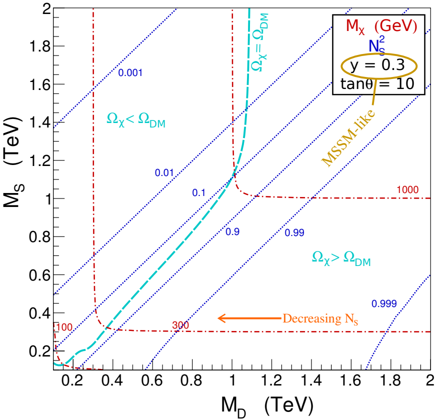
$$y_{D_1} = y\cos\theta \qquad\qquad y_{D_2} = y\sin\theta$$

- $y \approx g'/\sqrt{2}$ for bino-Higgsino; $y = \lambda$ for singlino-Higgsino

Relic Density

Relic density is controlled by mixing

- Pure singlet has $\Omega_\chi \gg \Omega_{\rm DM}$
- Pure doublet has $\Omega_\chi = \Omega_{\rm DM}$ at $M_\chi \approx 1.1$ TeV
- Mixture can have $\Omega_\chi = \Omega_{\rm DM}$ for any $M_\chi \lesssim 1.1$ TeV based n mixing angle



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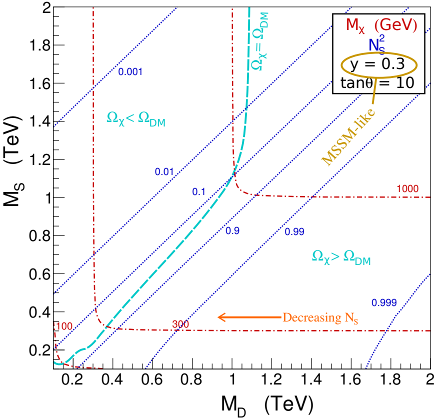
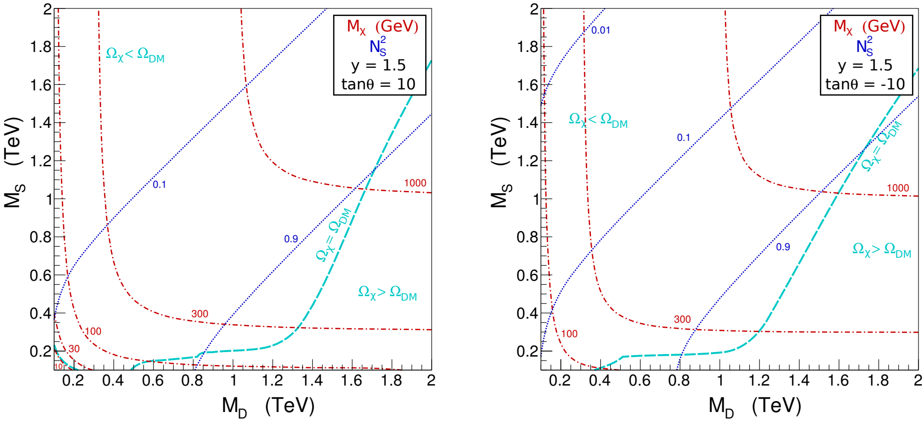


$\Omega_\chi\,(N_S)$ is nearly monotonic for fixed M_χ

- Singlet decouples for $N_S \to 0$
- "Annihilation thresholds" affects Ω_χ, particularly for large y

Relic Density for Large Coupling

Increasing y and changing θ also affect behavior



- Large Higgs coupling contributes somewhat to annihilation
- The induced Z-boson coupling is more important to relic determination

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The characteristic equation for the mass matrix is

$$\left(M_\chi^2 - M_D^2\right)\left(M_S - M_\chi\right) + \frac{1}{2} y^2 v^2 \left(M_\chi + M_D \sin 2\theta\right) \quad = \quad 0$$

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- Mass splitting is larger for $\tan\theta > 0$

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The corresponding Higgs coupling $c_{h\chi\chi}$ is

$$c_{h\chi\chi} = -\frac{y^2 v^2 \left(M_\chi + M_D \sin 2\theta\right)}{\left(M_D^2 - M_\chi^2\right) + 2M_\chi \left(M_S - M_\chi\right) + y^2 v^2/2}$$

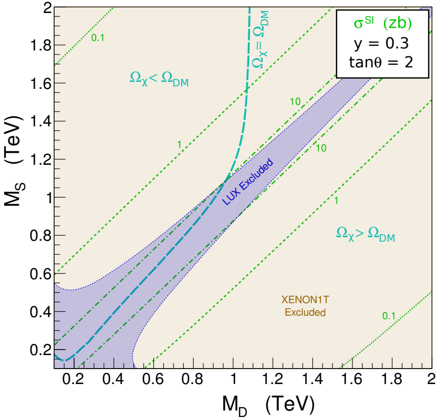
- $c_{h\chi\chi} \to 0$ for $y \to 0$ ***or*** $\left(M_\chi + M_D \sin 2\theta\right) \to 0$
- **"Blind Spot"** for direct detection if $y \neq 0$

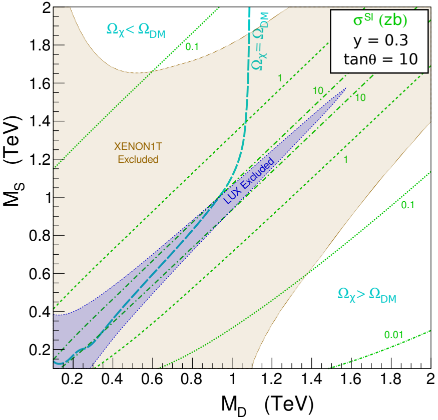
Cheung, Hall, Pinner, Ruderman (2012)

- Blind spot is only present for $\tan\theta < 0$

Direct Detection: $y = 0.3, \tan\theta > 0$

Bino-Higgsino-like with $\mu > 0$





No abundance re-scaling away from the thermal line

- Strong bounds on thermal region from LUX
- Exceptional reach for XENON1T

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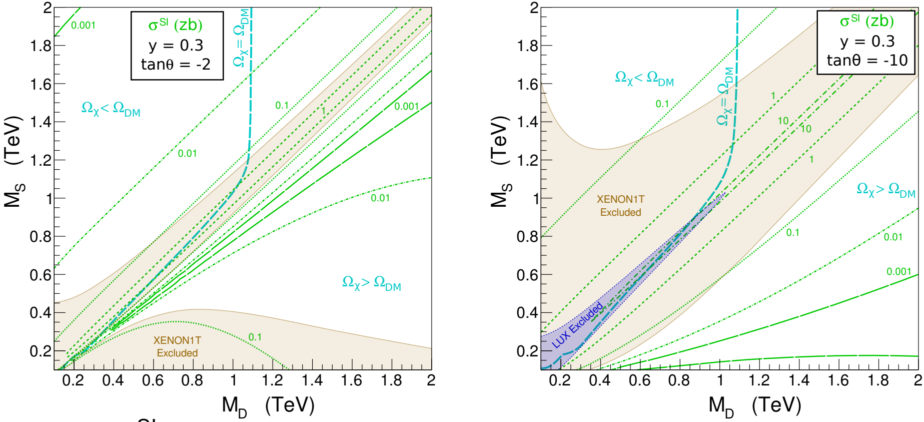
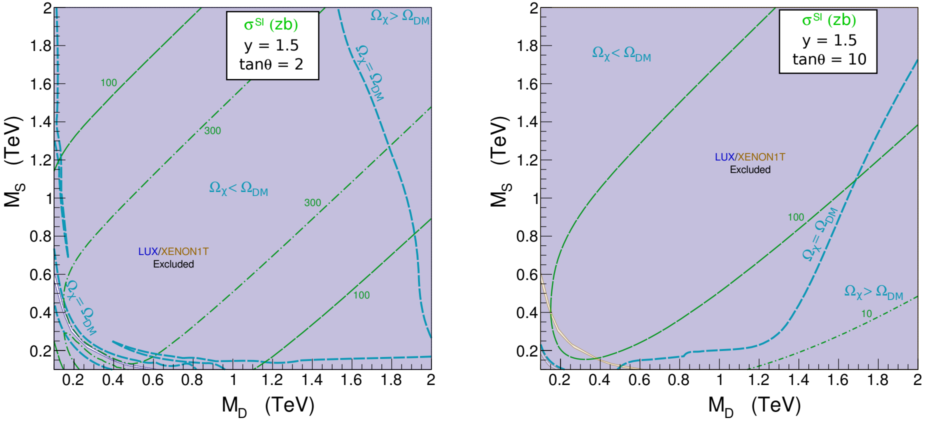


- σ^{SI} is generally suppressed
- Blind spot occurs for $M_S + M_D \sin 2\theta \approx 0$
- Much weaker bounds from LUX
- Reduced sensitivity at XENON1T

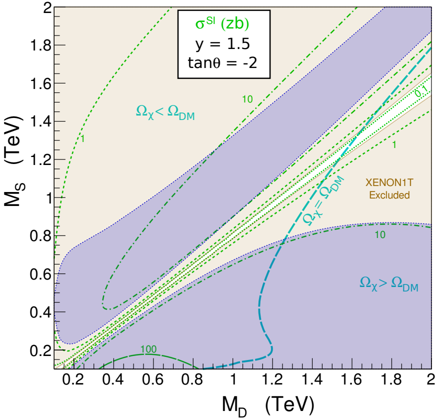
Direct Detection: $y = 1.5$, $\tan\theta > 0$

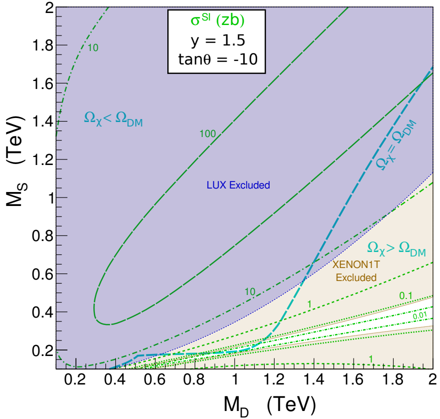


- Relic density contour behavior for $\tan\theta = 2$ results from annihilation channel thresholds and a large Higgs coupling
- LUX/XENON1T sensitivity cover almost the entire mass range
  - $\Gamma(H \to \mathrm{invis.}$ bounds should cover the low mass points

Direct Detection: $y = 1.5$, $\tan\theta < 0$

Blind spot remains even for large couplings





- Strong bounds from LUX and sensitivity at XENON1T outside the blind spot
- Portion of the $\Omega_\chi = \Omega_{\rm DM}$ line remain outside XENON1T sensitivity

Fixing the Relic Density

In WIMP models, the most interesting region is the $\Omega_\chi = \Omega_{DM}$ slice of parameter space

- Provides an explanation for all of dark matter without needing further candidates or high-scale physics
- Correlation often exist between early annihilation and current searches
    - Mixing produces both annihilation and a Higgs coupling for mixed DM

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For mixed DM, the parameter space reduction is valuable

- Four degrees of freedom $\{M_S, M_D, y, \tan\theta\}$ for singlet-doublet fermion
- Can gain insight into overall parameter space by fixing each parameter in turn to produce $\Omega_\chi = \Omega_{\mathrm{DM}}$

Well-Tempering

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- Tempering should be alleviated for nearly pure states
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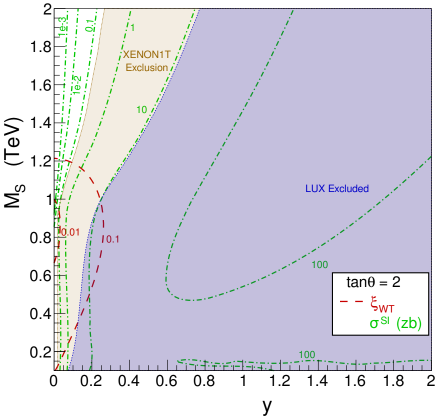
Defining a well-tempering measure indicates roughly how generic models with $\Omega_\chi = \Omega_{\rm DM}$ are

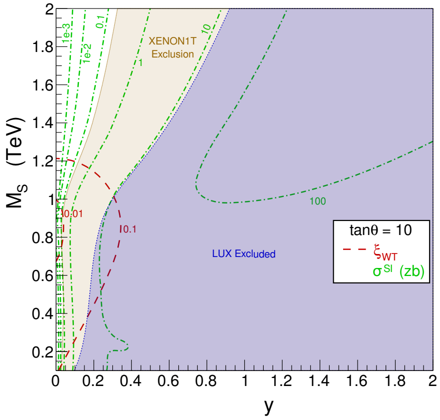
$$\xi_{\rm WT} = \left(\frac{N\,{\rm Tr}[\mathbf{M}^4]}{{\rm Tr}[\mathbf{M}^2]^2} - 1 \right)^{\frac{1}{2}}$$

- Equivalent to the fractional standard deviation of neutral particle masses-squared
- More robust than mass differences for large mixing terms

Singlet-Doublet Fermion with Fixed Relic Density

$\Omega_\chi = \Omega_{\rm DM}$ throughout the entire plane

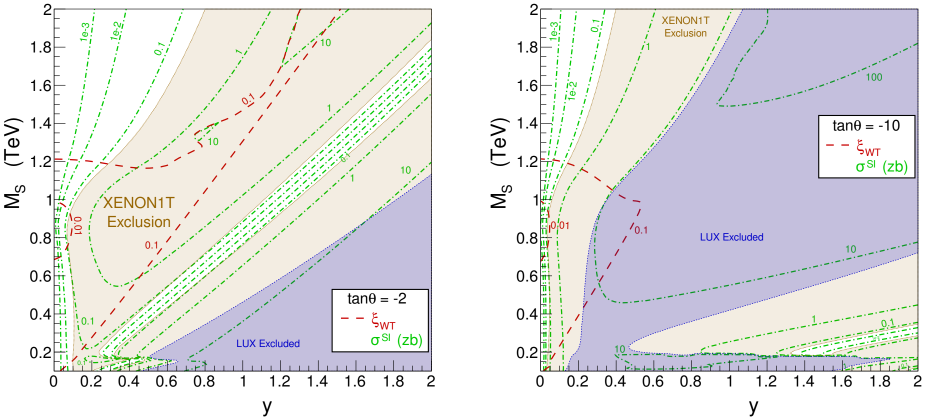




- XENON1T sensitivity reaches $y < 0.05$ for $M_S \lesssim 1$ TeV
- Surviving region exhibits $\xi_{\rm WT} < 0.1$ for surviving region for $M_S \lesssim 1.2$ TeV

Singlet-Doublet Fermion with Fixed Relic Density

Blind spots survive for tan $\theta < 0$



- Blind spots are located primarily at for larger couplings
- Significant regions evade XENON1T sensitivity with $\xi_{\rm WT} > 0.1$

Blind Spots and Fine-Tuning of the Higgs Coupling

The singlet-doublet fermion model cannot be excluded by spin-independent direct detection, even for low mass and large coupling

- Loop corrections shift the position of blind spots, but do not eliminate them

Hill and Solon (2013)

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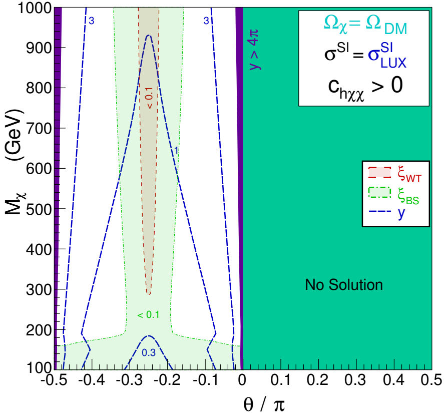
A fine-tuning measure for the blind spot is required

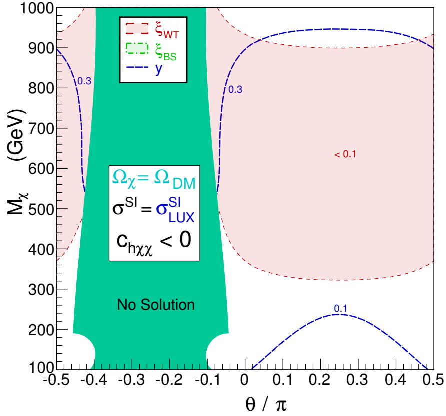
$$\begin{aligned} \xi_{\rm bs} &= \frac{|a+b|}{|a|+|b|} & \text{(GenericForm)} \\ &= \left|\frac{M_\chi + M_D \sin 2\theta}{M_\chi + M_D|\sin 2\theta|}\right| & \text{(Singlet} - \text{Doublet Fermion)} \end{aligned}$$

- $\xi_{\rm bs} = 1$ when no cancellations occur
- $\xi_{\rm bs} \to 0$ in the blind spot

Marginal Exclusion – LUX

All points have $\Omega_\chi = \Omega_{\rm DM}$ and lie along the LUX 90% upper limit



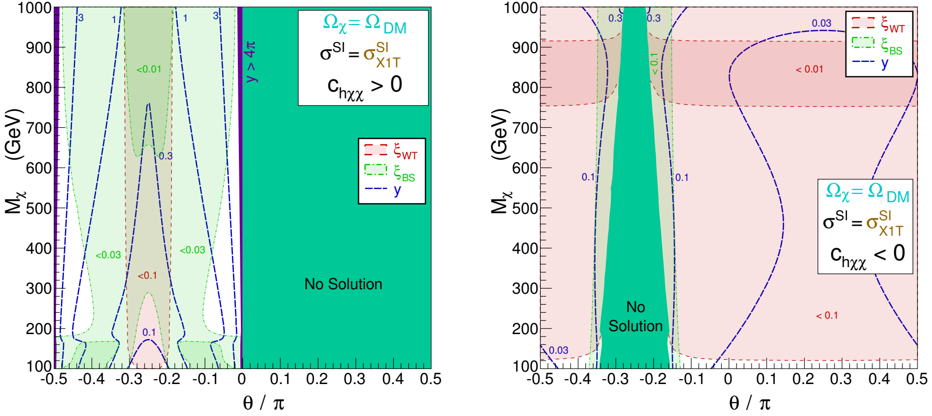


"Well-tempering and fine-tuning of $c_{h\chi\chi}$ required by LUX"

- $c_{h\chi\chi} > 0$ requires enhanced annihilation
- $c_{h\chi\chi} < 0$ depends upon mixing and coannihilation
- LUX allows large regions with $\xi_{\rm WT}, \xi_{\rm BS} > 0.1$

Projected Marginal Exclusion – XENON1T

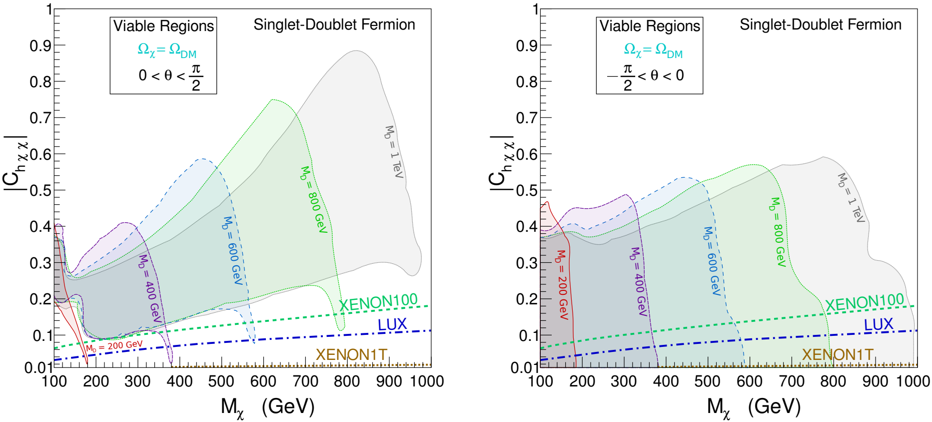
“Well-tempering and fine-tuning of $c_{h\chi\chi}$ at XENON1T reach”



- $c_{h\chi\chi} > 0$: $\xi_{\mathrm{BS}} < 0.1$ throughout
- $c_{h\chi\chi} < 0$: $\xi_{\mathrm{WT}} < 0.1$ for most of the plane

Summary of Singlet-Double Fermion

Allowed regions in the mass-coupling plane



- For $\tan\theta > 0$ only coannihilation regions with $M\chi \to M_D$ survive LUX
- For $\tan\theta < 0$ blind-spots occur, but require significant fine-tuning after XENON1T

Moving Beyond Singlet-Doublet Fermion

In general, any combination of states are possible

- So if you'll just bear with me for the next 10 hours...

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Will consider only two-state mixtures

- Simplicity
- Having 3+ states be relevant involves more well-tempering

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- Simplicity
- Having 3+ states be relevant involves more well-tempering

One state must be a singlet

- Viable masses for relic density are *generically* between the preferred masses of the two pure states
- $\Rightarrow$ Mass window is relatively large for two non-singlet mixed states

Moving Beyond Singlet-Doublet Fermion

Restrict attention to renormalizable mixing terms

- Non-renormalizable operators require integrating out other fields
- Leads to larger well-tempering
- Example: bino-wino mixing in the MSSM:

$$-\mathcal{L}_{\text{Mixing}} \sim \frac{h^2}{\mu}\tilde{B}\tilde{W} \qquad \text{(induced by Higgsino exchange)}$$

$$\xi_{\text{WT}} \sim \left(\frac{v^8}{\mu^4} + \left(M_{\tilde{W}}^2 - M_{\tilde{B}}^2\right)^2\right) / \left(M_{\tilde{W}}^2 + M_{\tilde{B}}^2\right)^2$$

$$\xi_{\text{WT}} \sim \frac{v^8}{\mu^4\left(M_{\tilde{W}}^2 + M_{\tilde{B}}^2\right)^2} \ll 1 \qquad \text{(significant mixing)}$$

Only singlet-doublet fermion, singlet-doublet scalar and singlet-triplet scalar survive these conditions

The Singlet-Doublet Scalar Model

Mixed singlet-doublet scalar models have most often been examined as a by-product of grand unification

M. Kadastik, K. Kannike, and M. Raidal (2009, 2010)

Cohen, Kearney, Pierce, Tucker-Smith (2012)

Field	Charges	Spin
S	$(\mathbf{1}, 0)$	0
D	$(\mathbf{2}, 1/2)$	0

- Only one doublet is requires
- Higgs couplings to pure states are allowed

- Doublet dark matter has multiple quartic Higgs couplings
- Trilinear mixing term

$$
\begin{aligned}
-\mathcal{L} &= \frac{1}{2} M_S^2 S^2 + M_D^2 \left|D\right|^2 + \frac{1}{2}\lambda_S S^2 \left|H\right|^2 + \lambda_D \left|D\right|^2 \left|H\right|^2 + \lambda'_D \left|HD^\dagger\right|^2 \\
&\quad + \frac{1}{2}\lambda''_D \left[\left(HD^\dagger\right)^2 + h.c.\right] + A\left[SHD^\dagger + h.c.\right]
\end{aligned}
$$

Simplifying the Parameter Space

7 free parameters: $\{M_S, M_D, \lambda_S, \lambda_D, \lambda'_D, \lambda''_D, A\}$

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$\{M_S, M_D, A\}$ define the mass scale and degree of mixing

$\{\lambda_D, \lambda'_D, \lambda''_D\}$ differ primarily in splitting between the doublet states

$$
\begin{aligned}
\mathbf{M}^2 &= \begin{pmatrix} M_S^2 + \frac{1}{2}v^2\lambda_S & Av & 0 \\ Av & M_D^2 + \frac{1}{2}v^2\left(\lambda_D + \lambda'_D + \lambda''_D\right) & 0 \\ 0 & 0 & M_D^2 + \frac{1}{2}v^2\left(\lambda_D + \lambda'_D - \lambda''_D\right) \end{pmatrix} \\
M_\pm^2 &= M_D^2 + \frac{1}{2}v^2\left(\lambda_D + \lambda''_D\right)
\end{aligned}
$$

Take $\lambda'_D = \lambda''_D = 0$ for simplicity

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$$M_{\pm}^2 = M_D^2 + \frac{1}{2}v^2\left(\lambda_D + \lambda''_D\right)$$

Take $\lambda'_D = \lambda''_D = 0$ for simplicity

$\{\lambda_S, \lambda_D\}$ are both important only for mixed states, so $\lambda_S = \lambda_D = \lambda$ is a reasonable simplification for most of parameter space

Features of Singlet-Doublet Scalar Dark Matter

Higgs coupling has both mixing and non-mixing contributions

$$
\begin{aligned}
a_{h\chi\chi} &= \frac{1}{2}v\left(\lambda_S + \lambda_D + \lambda_D' + \lambda_D''\right) - \frac{2vA^2 + \frac{1}{2}v\left(\tilde{M}_S^2 - \tilde{M}_D^2\right)\left(\lambda_S - \lambda_D - \lambda_D' - \lambda_D''\right)}{\sqrt{\left(\tilde{M}_S^2 - \tilde{M}_D^2\right)^2 + 4v^2A^2}} \\
&= \lambda v - \frac{2vA^2}{\sqrt{\left(M_S^2 - M_D^2\right)^2 + 4v^2A^2}}
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Blind spot only occurs for non-zero λ

- Produced by cancelling mixing and non-mixing term

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\end{aligned}
$$

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- Produced by cancelling mixing and non-mixing term
- Only $\lambda_D+\lambda'_D+\lambda''_D$ combination appears
- $a_{h\chi\chi}\to\lambda_S v$ or $\left(\lambda_D+\lambda'_D+\lambda''_D\right)v$ away from mixed region
  - Deviating from $\lambda_S=\lambda_D=\lambda$ assumption has little visible effect in plotted regions

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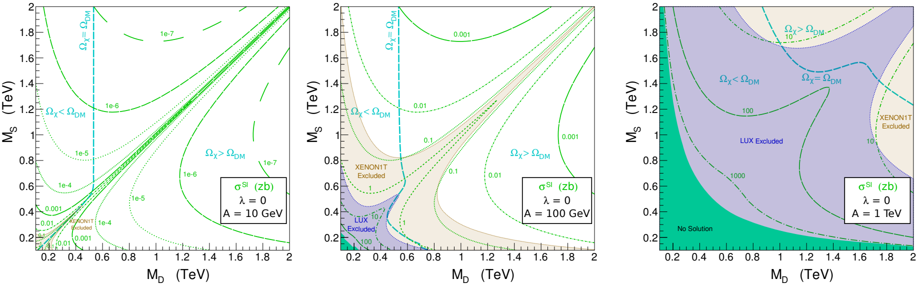
The well-tempering and fine-tuning measures are

$$
\xi_{\rm WT} = \frac{\sqrt{\left(M_S^2-M_D^2\right)^2+4v^2A^2}}{\left(M_S^2+M_D^2+\lambda v^2\right)} \qquad \xi_{\rm BS} = \frac{\left|\lambda v\sqrt{\left(M_S^2-M_D^2\right)^2+4v^2A^2}-2vA^2\right|}{|\lambda v|\sqrt{\left(M_S^2-M_D^2\right)^2+4v^2A^2}+2vA^2}
$$

Direct Detection for $\lambda = 0$

Higgs-mediated annihilation is important for scalars!

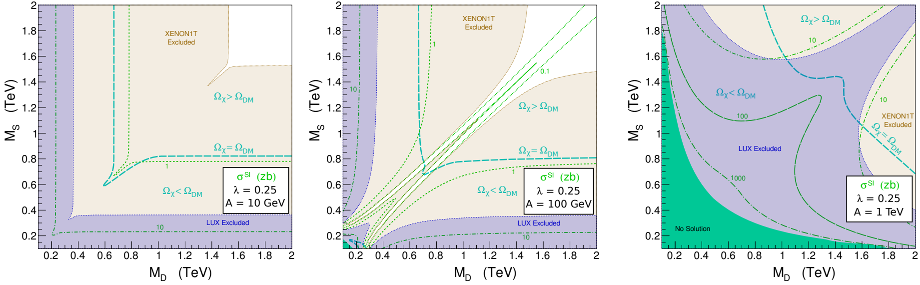


- For low to moderate coupling, asymptotic pure doublet behavior survives
- No p-wave suppression of Higgs-mediated contribution $\Rightarrow$ Higgs-mediated annihilation dominates for $M_S < M_D$, and entire plane for large coupling
- High-mass regions with $\Omega_\chi = \Omega_{\rm DM}$ survive LUX

Direct Detection for $\lambda = 0.25$

$\Omega_\chi = \Omega_{\rm DM}$ is possible without mixing

- $M_D \approx 650$ GeV or $M_S \approx 800$ GeV for $\lambda = 0.25$



- $\lambda > 0$ produces a suppression of the Higgs coupling
- Regions with $\Omega_\chi = \Omega_{\rm DM}$ survive for moderate mixing terms
- $\lambda > 0$ is generically favored for stability

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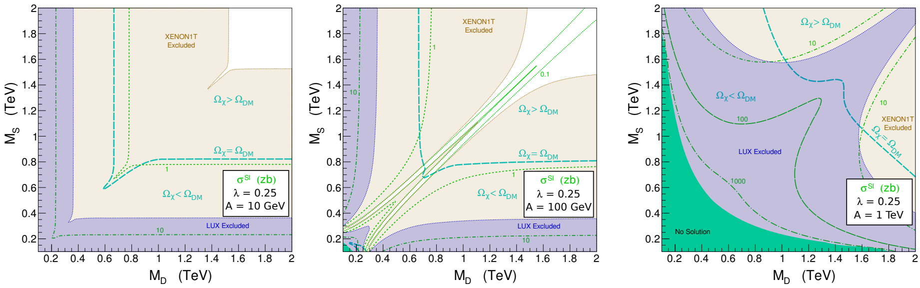

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- Regions with $\Omega_\chi = \Omega_{\mathrm{DM}}$ survive for moderate mixing terms
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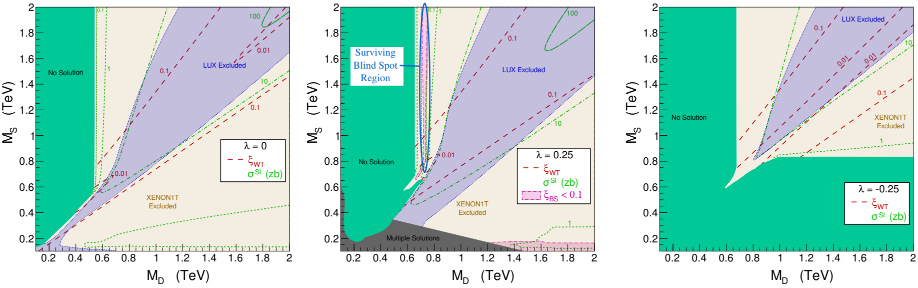
$\lambda < 0$ has similar behavior but no blind spot

Singlet-Doublet Scalar with Fixed Relic Density

$\Omega_\chi = \Omega_{\mathrm{DM}}$ is fixed by varying A

- $\Omega_\chi(A)$ is the most monotonic of possible choices

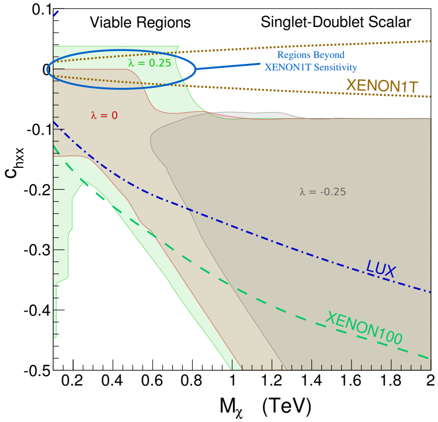


- LUX constraints are strong and *improve at large mass*
  - Above $M_D \approx 500$ GeV some Higgs coupling is needed for annihilation
- XENON1T sensitivity covers almost all parameter space
- Pure doublet survives for $\lambda = 0$, as does a blind spot with $\xi_{\mathrm{BS}} < 0.1$ for $\lambda = 0.25$

Summary of Singlet-Doublet Scalar

Thermal singlet-doublet scalar dark matter is constrained by LUX, and mostly within XENON1T reach

- Pure doublet remains viable for $M_\chi \lesssim 500$ GeV
- Blind spots remain for $\lambda > 0$ but require significant fine-tuning
  - Coverage of parameter space was more limited than singlet-doublet fermion case
  - $\lambda > 0$ allows $c_{h\chi\chi} = 0$ for $M_\chi > 500$ GeV
  - Larger values of λ increase the viable mass, but require more fine-tuning



$$c_{h\chi\chi} = a_{h\chi\chi}/M_\chi$$

The Singlet-Triplet Scalar Model

Mixed singlet-triplet scalar models have also been examined as a consequence of grand unification

Fischer and van der Bij (2011, 2013)

- Mixing term is a quartic rather than trilinear
- Triplet has $Y = 0$
- No $ZZ\chi\chi$ coupling
- $W^+W^-\chi\chi$ couplings is stronger by a factor of four

Field	Charges	Spin
S	$(\mathbf{1}, 0)$	0
T	$(\mathbf{3}, 0)$	0

- Triplet is a real scalar
- Two charged triplets are also possible, but not considered here

$$
\begin{aligned}
-\mathcal{L} &= \frac{1}{2}M_S^2 S^2 + M_T^2 \,\mathrm{tr}\left(T^2\right) \\
&\quad + \frac{1}{2}\lambda_S S^2 \left|H\right|^2 + \lambda_T \,\mathrm{tr}\left(T^2\right)\left|H\right|^2 + \kappa S H^\dagger T H
\end{aligned}
$$

Features of the Singlet-Triplet Scalar Model

Five free parameters: $\{M_S, M_T, \lambda_S, \lambda_T, \kappa\}$

- Set $\lambda_S = \lambda_T = \lambda$ for simplicity

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Higgs coupling is similar to singlet-doublet scalar

$$a_{h\chi\chi} = \lambda v - \frac{\frac{1}{4}\kappa^2 v^3}{\sqrt{\left(M_S^2 - M_T^2\right)^2 + \frac{1}{4}\kappa^2 v^4}}$$

- Mixing part is roughly twice the size of the singlet-doublet case for equivalent mass spectrum

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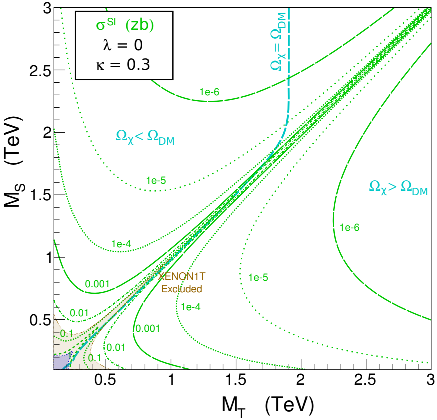
- Mixing part is roughly twice the size of the singlet-doublet case for equivalent mass spectrum

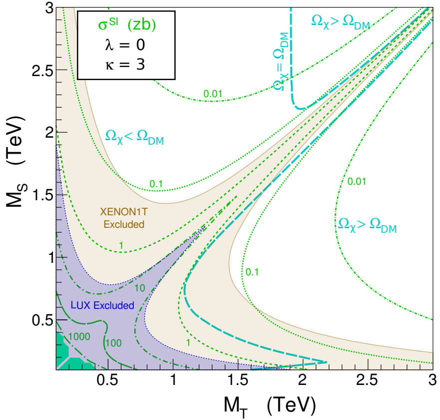
Fine-tuning measures also similar to singlet-doublet

$$\xi_{\rm WT} = \frac{\sqrt{\left(M_T^2 - M_D^2\right)^2 + \frac{1}{4}\kappa^2 v^4}}{\left(M_S^2 + M_T^2 + \lambda v^2\right)} \qquad \xi_{\rm BS} = \frac{\left|\lambda v \sqrt{\left(M_S^2 - M_T^2\right)^2 + \frac{1}{4}\kappa^2 v^2} - \frac{1}{4}\kappa^2 v^3\right|}{|\lambda v| \sqrt{\left(M_S^2 - M_T^2\right)^2 + \frac{1}{4}\kappa^2 v^2} + \frac{1}{4}\kappa^2 v^3}$$

Direct Detection for $\lambda = 0$

Annihilation is much stronger for singlet-triplet scalar!





- A pure triplet has $\Omega_\chi = \Omega_{\rm DM}$ for $M_T \approx 2$ TeV
- Quartic mixing term produces strong $\chi\chi \to hh$ annihilation

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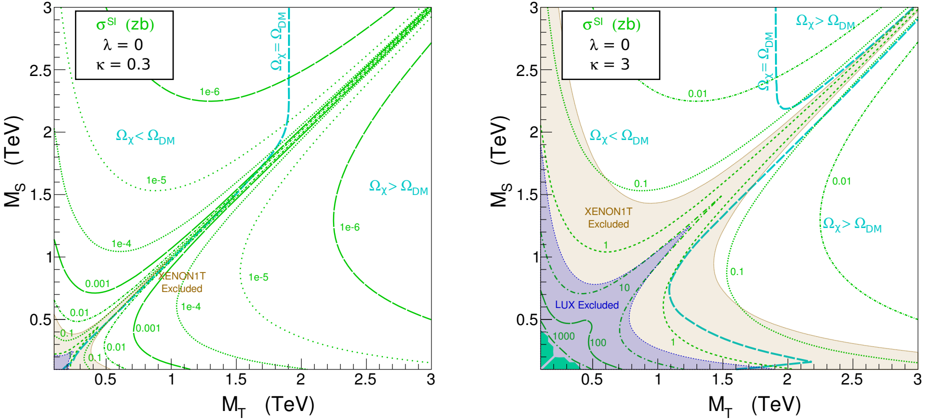
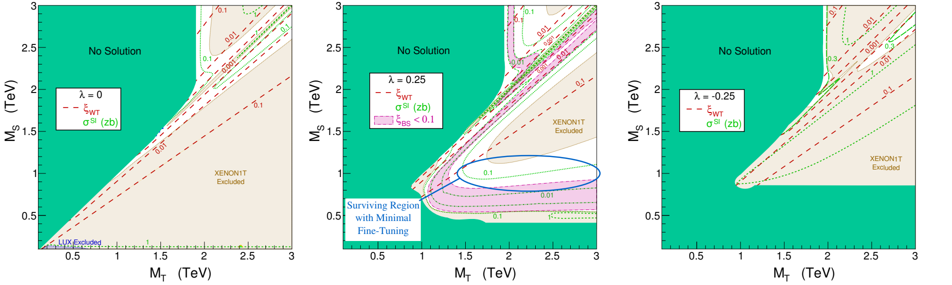


- A pure triplet has $\Omega_\chi = \Omega_{\rm DM}$ for $M_T \approx 2$ TeV
- Quartic mixing term produces strong $\chi\chi \to hh$ annihilation

Effect of $\lambda \neq 0$ similar to singlet-doublet case

Singlet-Triplet Scalar with Fixed Relic Density

Detection prospects weaken significantly for singlet-triplet dark matter

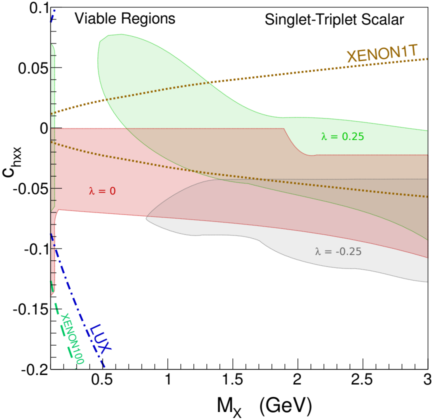


- LUX has almost no constraining power
- Pure triplet avoids XENON1T sensitivity for all values of λ shown
- Large blind spots survive with $\xi_{\mathrm{WT}}, \xi_{\mathrm{BS}} > 0$ for $\lambda = 0.25$

Summary of Singlet-Triplet Scalar

Singlet-triplet scalar is less constrained by direct detection than other models considered

- Strong annihilation drives thermal region to larger M_χ
- $c_{h\chi\chi} = 0$ possible for a larger range of M_χ and λ
- Very weak constraints from LUX and significant regions lie outside XENON1T sensitivity



$$c_{h\chi\chi} = a_{h\chi\chi}/M_\chi$$

Conclusion

- Now is an interesting time for dark matter!
  - A number of conflicting results make the field ripe for theory consideration
- Higgs-mediated models are particularly relevant for direct detection
- Mixing of multiple $\mathrm{SU}(2) \times \mathrm{U}(1)$ states implies a Higgs coupling
- Direct detection prospects good for thermal singlet-doublet models
- Significant portions of thermal singlet-triplet scalar parameter space avoid XENON1T sensitivity

Future Directions

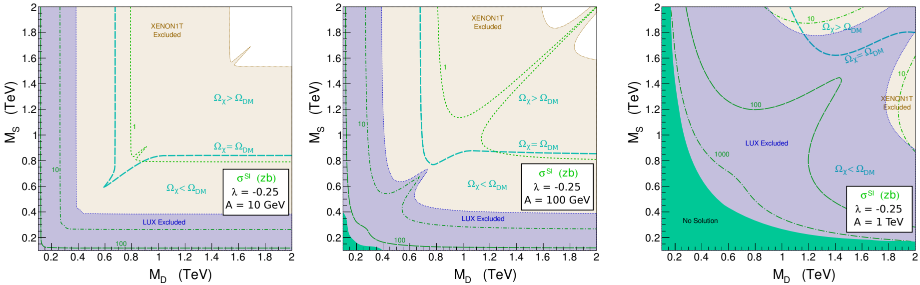
- Spin-dependent
  - Occurs at tree level only for singlet-doublet fermion
- Indirect detection constraints
- $\Gamma(h \to \mathrm{invis.})$ and other precision constraints
- Consider non-perturbativity bounds
  - May limit maximum mass for singlet-triplet scalar
- Examine stability bounds for scalar models
- Examine mixing of higher dimensional representations
- Allow for non-renormalizable operators (singlet-quadruplet, singlet-quintuplet, etc.)
- Compare with collider constraints
  - Many more possible channels than monojets from effective operators

Backup Slides

Direct Detection for $\lambda = -0.25$

Location of $\Omega_\chi = \Omega_{\rm DM}$ is similar to $\lambda = 0.25$

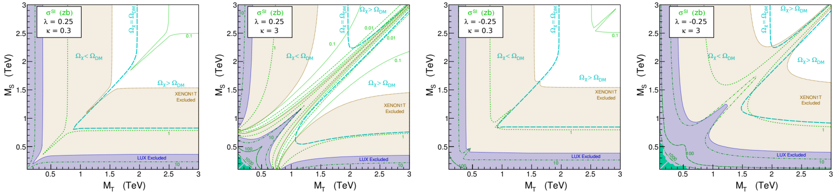
Enhanced Higgs coupling shifts the contour to higher masses



- Stronger constraints from direct detection
- Some of the $\Omega_\chi = \Omega_{\rm DM}$ contour survives for large mass and mixing terms
- $\lambda < 0$ is weakly disfavored by stability

Direct Detection for $\lambda \neq 0$

$\lambda \neq 0$ provides for $\Omega_\chi = \Omega_{\mathrm{DM}}$ without mixing



- $\lambda = \pm 0.25$ does not meaningfully affect the contour position for a pure triplet
- Blind spot behavior remains for $\lambda < 0$
- $\chi\chi \to hh$ remains dominant for $\lambda \neq 0$
- Strong annihilation weakens direct detection of thermal region even for $\lambda > 0$